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(54) Linear actuator.

(57) The present invention is useful for quickly releasing an object which is being moved by an actuator. Generally actuators of the piezoelectric type move objects slowly. For applications where an object must be quickly moved such as when releasing brakes or reinserting a control rod in a reactor core an actuator should have a quick release feature. The invention uses a set of actuators which contact a bolt and moves the bolt with smooth walking motion. The bolt in turn is driven by the actuators such that it engages an object with smooth walking motion to move or position the object. When the object is to be released the actuators are removed from contact from the bolt thereby releasing the object.

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Background of the Invention

Applicant's patent number 4,928,030 teaches two- and three-axis piezoelectric actuators that position an object such as a rod or motor shaft by walking traction. A lifter piezoelectric actuator portion positions the actuator's traction member perpendicular to the object's surface. A tangenter piezoelectric actuator portion positions the actuator's traction member tangential to the object's surface. Lifter and tangenter portions of an actuator are integrally constructed and independently electrically controllable. A walking cycle consists of activating the lifter to apply a predetermined normal force between the traction member and the object while the tangenter translates the traction member at a speed equal to the surface speed of the object. During application and removal of normal force, no mechanical work is done by the traction member on the object. As the normal force is applied, a tangential strain is added to the tangenter portion. The product of the tangential force and the tangential distance traveled during the power stroke portion is the work done on the object. The work done per unit time, averaged over a complete cycle, is the power transmitted to the object.

At the end of the power portion of the cycle the tangential strain is removed as the normal force is removed by the lifter, still maintaining zero relative speed between object and traction member. As the traction member leaves the object's surface, the traction member retraces, that is, it reverses tangential stroke direction and changes speed until the opposite extreme tangential position is reached, thereby preparing for a new stroke. This is a smooth walking cycle because sliding is avoided. A pair of actuators alternately executes walking cycles, one actuator performing a power stroke while the other retraces. A predetermined coordinated positioning of the traction members of both actuators results in smooth walking. Smooth walking is defined as uninterrupted and smooth tractional power transmission without sliding.

The piezoelectric materials are generally electrically polarized ferroelectric ceramics. This class of materials is relatively brittle, having relatively little tensile strength. In addition, the temperature above the usual room temperature at which electrical polarization is irreversibly lost, usually called the Curie temperature, is relatively low. These physical properties are a detriment in some applications of walking actuators. Patent 4,928,030 also teaches the use of relatively high applied voltages to achieve desirably large mechanical strokes. High voltages are a disadvantage in the context of solid state electronic drive devices, such devices having evinced more efficient operation with low voltages with relatively large currents.

Applicant's copending application serial number 07/488,548 teaches the use of Fourier generation of nonsinusoidal mechanical wave forms needed for smooth walking. The teachings are primarily directed toward piezoelectric actuators, but are also directed toward electromagnetic actuators that function in a manner similar to piezoelectric ones. The benefits taught are relatively high electrical efficiency derived from resonant excitation of actuator portions, and relatively high electrical stability not normally associated with power amplifiers that drive preponderantly reactive electrical loads.

Objects of the Invention

The primary object of the present invention is a walking releasing actuator that forcefully and precisely positions an object through distances which are great relative to a single actuator stroke, yet releases the object with clearance that is large relative to said actuator stroke.

Other objects are:

operate in hazardous environments such as in seawater, near radioactive materials, in space vacuum and the like;

to impart relatively large forces at moderate speeds to a positioned object;

to independently electrically control force and speed of positioning;

to forcefully position an object without bearings or springs, and with relatively few life-shortening mechanisms such as rubbing;

to forcefully position and release an object in a linear direction by simultaneous independent electrical control of multiple angularly disposed actuator action directions;

to forcefully position and release an object in three orthogonal directions of translation by simultaneous independent electrical control of multiple angularly disposed actuator action directions;

to forcefully position an object without lubricants and without lubricant seals;

to forcefully position an object using moderate voltages;

to forcefully position an object using relatively high internal energy density obtained through the use of superconductors in cryogenic applications;

to position an object with structural rigidity comparable to a solid apparatus;

to position an object by traction that is tolerant of traction surface roughness and waviness;

to position an object by tractive action that cleans the traction surface;

to operate as a generator to convert mechanical energy into electrical power;

to position an object in a micro- and in a zero-gee environment using normal tractive forces supplied by the actuators without external normal forcing

means;

to operate in a fail-free mode allowing increased reliability through the use of multiple positioners walking on a common positioned object;

to operate in a fail-locked mode in applications requiring mostly forcefully held static positions and minimum cooling;

to provide an actuator manufacturing method resulting in relatively high positioning energy density through microminiaturization of actuator components;

to provide an actuator having no ohmic contacts or exposed electrical conductors;

to provide a positioning apparatus having no sliding electrical commutator;

to scale actuator size from relatively small to very large in accordance with the requirements of a large class of transducer applications;

to operate at relatively high energy density using forced fluid convection cooling in interconductor interstices;

to operate at relatively high energy density using forced fluid convection cooling through channels internal to actuator components, also allowing vacuum and space operation without exposure or loss of coolant;

to operate in intense ionizing radiation with relatively long life and little nuclear transmutation;

to be constructed with relatively light weight materials;

to operate with relatively high electrical efficiency by means of magnetic flux concentrated by permeable portions;

to operate with relatively high electrical efficiency by means of magnetic flux interacting with magnetized portions;

to operate with relatively high electrical efficiency by means of piezoelectric and ferroelectric materials;

to operate with relatively high electrical efficiency by means of hybrid piezoelectric and magnetic actuator materials;

to operate with high electrical efficiency in combination with Fourier stimulation;

to operate with relatively high mechanical efficiency by means of smooth walking; and

to operate with relatively high system efficiency by smooth walking combined with Fourier stimulation.

Brief Description of Figures

Figure 1 is a perspective drawing of an electric walking actuator having a layered body and a traction member.

Figure 2 is a perspective partially ghosted view of an actuator assembly of the present invention.

Figure 3 is a plan view of a dual pair positioner of the present invention.

Figure 4 is a side view of an actuator assembly showing tractive positioning.

Figure 5 is a side view of an actuator assembly releasing a positioned object.

Figure 6 is a side view of a variant of an actuator assembly having additional releasing safety features.

Figure 7 is a perspective ghosted view of a positioner variant including rollers in place of a set of actuators.

Figure 8 is a plan view of a positioner embodiment having three pairs of actuators for kinematic stability.

Figure 9 is a schematic positioner system diagram using a preferred electric drive means for nuclear reactors and other pressurized apparatus.

Figure 10 is a half cross sectional view of a disk brake.

Detailed Description

Referring to Figure 1 , shown is a perspective view of a two-axis actuator generally indicated 2, comprising a mounting base surface portion 4, a traction surface portion 6 of traction member 8, and layered actuator body portions 10, 12 of electromechanical transducer material connected to an electrical source by leads 22. The actuators used in this invention may also be thermal, magnetic or powered by some other means. The actuator body material forcefully positions traction surface 6 in predetermined directions in response to the application of a predetermined magnitude and polarity of applied electric signal. Body portion 10 causes positioning of traction member 8 in direction 16 and is hereinafter referred to as a lifter. Body portion 12 positions traction member 8 in direction 20 and is hereinafter referred to as a tangenter. A third body portion (not illustrated), similar to portion 12, acts in a third direction 18 at an angle to the action of portion 12, thus constituting a three-axis actuator. Traction member positioning directions 16, 18, and 20 may be orthogonal, and alternatively may act along predetermined relative angular directions.

Referring to Figure 2, shown partially ghosted is an actuator assembly generally indicated by arrow 23, comprising housing 36, pairs of actuators (Fig. 1) 24 and 26, bolt 28 and positioned object 34. Actuators 24 and 26 are attached by mounting surfaces (4 of Fig. 1) to inner surface portions of housing 36. Bolt 28 is a bar-like member having two opposing traction surfaces, one (30) of which is illustrated. Surfaces 30 are in tractive contact with actuator traction members 8. Traction normal force is entirely supplied by actuator lifters (10 of Fig. 1). On application of traction normal force, bolt 28 is positioned in direction 20 by actuator tangenters

(12 of Fig. 1). During actuator walking, actuators 24 forcefully position bolt 28 in direction 20 while actuators 26 are retracing. Retracing entails lifting the traction members 8 clear of traction surface 30 and moving them tangentially to the opposite extreme of tangential movement in preparation for a new walking step. Actuator sets 24 and 26 act cyclically and alternately.

Bolt 28 is moved in direction 20 until bolt traction surface 32 applies a predetermined normal tractive force to positioned object 34. Upon applying the predetermined normal force to positioned object 34, walking of actuators 24 and 26 on bolt 28 ceases and coordinated actuator lifter and tangenter action cause bolt traction surface 32, in conjunction with other opposing actuator assemblies (see fig. 3 and 8) to walk on and thereby forcefully position object 34 in directions 16.

If the traction surface of object 34 is rough or wavy, additional actuator walking steps are made to reposition bolt 28 and reapply the predetermined tractive normal force. A positioner of the present invention comprises at least two pairs of actuator assemblies. Any number of actuator assemblies may be used to position an object. Bolts may retrace singly and in any combination in accordance with a predetermined operation time schedule. The use of many actuator assemblies 23 renders the positioner relatively tolerant of a failure of one to a few actuator assemblies.

Referring to Figure 3, shown is a plan view of two pair of walking actuator assemblies 23 tractively positioning object 34 by alternating tractive strokes of opposing bolts 28. Normal forces 38 of one bolt pair accompanies a forceful positioning stroke 16 (Fig. 2), while bolt retractions 40 accompany bolt retraces. Figure 8 is a plan view of a three-pair positioner using the same numbering and function description as that of Fig. 3. Object 34 is positiond by two alternately acting groups of three actuators 23 in this example.

Figure 4 is a side view of one actuator assembly of Fig. 3 applying bolt normal force 38 to positioned object 34, while actuator lifters forcefully position in direction 42. To move the object 34, lifters on one side of bolt 28 decrease in thickness as the lifters on the opposite bolt side increase in thickness.

Figure 5 shows a side view of the actuator assembly of Fig. 4 just after actuator lifters have released their grip on the bolt, illustrating bolt release in direction 40 that precedes freeing of object 34, in this example free fall of object 34 by gravity, but it may be some other external forcing agency, in direction 44. Bolt retraction stroke 46 is predetermined to provide free fall clearance in accordance with a particular application. A diverse class of applications require a clearance 46 that is equivalent to hundreds to thousands of actuator walking steps.

Figure 6 is a side view of a variant of the actuator assembly of Fig. 4, illustrating a ski nose bolt portion 48 and a spring 49 (actuator 23 omitted for clarity). Ski nose 48 retracts a released bolt by contact with a ridge 47, or some other protrusion extending from the released object 34, the spring being optional. The spring, with or without the ski nose, is used in applications benefitting from positive bolt retraction that avoids traction surface damage due to sliding.

Figure 7 illustrates partially a ghosted variant of the actuator assembly of Fig. 2, retaining in part the numbering and functions of Fig. 2, this variant having hollow rollers 50 in place of the upper sets of actuator pairs of Fig. 2, and a similar variant (not illustrated) having solid rollers. The hollow roller variant is used for a diverse class of applications having force on object 34 predominantly in one direction 52, such as the weight of positioned object 34, the advantage being fewer actuators. In operation, actuators 24 apply forcing and retrace strokes to the object alternately with actuators 26 while rollers provide an elastic compliance and maintain normal force between actuators and the bolt regardless of the state of electric activation of actuator lifters. The hollow springy roller embodiment allows actuator lifter strokes to be no larger than those required to clear retracing actuator traction members as neighboring traction members assume the normal load. The hollow roller embodiment is relatively tolerant of manufacturing errors. A predetermined roller spring constant prevents the complete release of the bolt, therefore requiring the actuators to control bolt position in direction 20 at all times. The solid roller embodiment has normal force supplied solely by the action of actuator lifters. The solid roller embodiment is capable of relatively great static and positioning loads, and provides complete bolt freedom when lifters are activated to their minimum lift stroke. The solid roller embodiment requires relatively precise manufacturing.

Figure 9 is a schematic diagram of a control system for the positioner of the present invention. The control system comprises but is not limited to electric power source 54, positioning electric criteria 56, coupling means 58, signal and power conditioner 62, transmitter 68, receiver 72, and controller 74. The positioner is shown with three pair of actuator assemblies 23 positioning an object 34. Electric power 54 has positioning criteria 56 superimposed thereon by coupler 58, the coupling being sent to the signal and power conditioner 62 via one or more wires 60. Signal and power conditioner 62 supplies signals and power in a form suitable to drive transmitter 68. Transmitter 68 may

be the primary of an inductive transformer. Receiver 72 may lie inside a pressure or containment vessel 70 that is relatively more reliable when the number of vessel wall penetrations is reduced. Receiver 72 collects and forwards transmitted power and positioning criteria to controller 74. Controller 74 separates positioning criteria from the electrical power. Positioning criteria are temporarily stored, to be further conditioned and directed to controller portions that activate actuators of the positioner. System variants may also store electrical power. These latter controller portions distribute the separated electric power to the actuators in accordance with the requirements of the positioning criteria. Sensors internal to the actuators inform the controller by means of multiconductor cable 78 of the state of force and relative actuator segment position in the positioner. The controller uses sensor data to minimize error signals of actuators in comparison to positioning criteria. System components, including the positioner, located internal to the vessel are designed to sustain the environment of the particular application.

A relatively severe background of ionizing radiation urges the use of magnetic actuators having potting or hermetic sealing appropriate with the particular application. Some piezoelectric actuators may be less tolerant of radiation, or may have a relatively narrow operating temperature range, but are inherently rigid, even when no electric drive is applied. Rigidity is an advantage in uncooled applications.

Figure 10 is a half cross section view that is essentially symmetric about an axis 86 of rotation of a disk brake embodiment of the present invention, comprising at least one releasing actuator assembly generally indicated 23, vented brake disk 82, and actuator support means 36. Actuator assembly 23 consists of walking actuators 2 connected to and supported by support means 36, and releasable means 28. Releasable means 28 is connected to brake pads 84 and optionally by intervening thermal isolation pads 80. Application of predetermined electric signals by way of connecting electrical terminals 76 causes actuators 2 to walk releasable means 28 in directions 20 in order to vary the squeezing force between brake pads 84 that affects braking action on disk 82 through friction on disk friction surfaces 32. In a preferred variant of the embodiment removal of all electrical signals to actuators 2 releases releasable means 28 which then translates guideably in direction 20 away from the disk, allowing the disk to coast without rubbing. A spring means (not illustrated) may also be added to releasable means 28 to assure rubless coasting. Another preferred embodiment uses stored electrical energy of the controller 74 means described for Figure 9 to apply and maintain maximum braking force in the event of predetermined conditions, such conditions including but not necessarily limited to loss of the main source of electrical power, accident, failure of a component of apparatus ancillary to the disk brake system and the like.

The advantage of the embodiment illustrated in Figure 10 is the travel distance in directions 20 provided by the walking action of actuators 2. The travel distance is very large in comparison to the length of a single step of actuator 2. The large stroke range in directions 20 is essential to compensate for wear at friction surfaces 32, changes in dimensions due to thermal expansion, bearing clearances, and other conditions known to change braking geometry during normal use, particularly heavy use. Movement perpendicular to direction 20 of member 28 by lifters of actuators 2 more evenly distributes wear asperities at surfaces 32.

Brakes appropriate to very heavy use, such as those that stop the Space Shuttle Orbiter and similar craft, convert thousands of horsepower to heat. The heat is essentially restricted to the vicinity of the friction pads 84, and largely prevented from conducting, convecting or radiating to actuators 2 by thermal isolators 80. Isolators consist of strong, heat resistant pads of material having low thermal conductivity such as foamed ceramic composites, laminates of carbon of graphite fiber with inorganic matrix, and such like. Those versed in the related arts will appreciate the use of vents in the disk between friction surfaces 32 that disperse heat while the disk is rotating, and will recognize the use of forced convection cooling of brake disks at rest by auxiliary fluid application means.

All embodiments of the present invention use electric currents. Actuator conductor circuits have preponderantly reactive, usually a combination of capacitive and inductive, electrical impedance. Actuator activation by an electric drive means circulates a relatively large quantity of electrical power, only a small fraction of which is converted to mechanical work during walking and positioning in most applications. Relatively high actuator system electrical efficiency obtains when the electrical drive means conserves power during circulatory activation. Given the typical output component resistance of a driver, a drive means that passes converted as well as reactive power through its output components will perform less efficiently than another drive means that passes only converted power.

The preferred drive means for the present invention is Fourier stimulation and is intended to be included in the controller (74 of Fig. 9). In a device having one or more pairs of actuators, each actuator portion having multiple layers, subsets of actuator layers of one actuator are electrically con-

nected in a circuit with the corresponding layers of another like actuator. Ancillary reactances are used when a single actuator or a group of electrically connected actuators is to be independently stimulated. Also connected in each circuit is a coupling and stimulating means such as a capacitive or inductive influence. An actuator subset may include a single layer or a group of layers. Preferably, a stimulated circuit includes one or more pairs of actuators. Each subset is stimulated in electrical (but not mechanical) resonance at a predetermined frequency and amplitude. Each subset therefore contributes a sinusoidal mechanical stroke portion to the action of the whole actuator. The inductances of actuators may be advantageously used as components of the electric drive means. The traction member of each actuator is forcefully positioned with the mechanical stroke that is the sum of the subset forceful stroke contributions. Subset stimulation frequencies and amplitudes are selected in accordance with Fourier rules for a particular nonsinusoidal mechanical stroke wave form, for example, that wave form appropriate to smooth walking. The smooth walking lifter stroke wave form is generally a rectangular wave, while the tangenter stroke wave form is a notched symmetric triangle wave. The notches provide the transfer of mechanical power to the bolt during the forcing stroke portion while the wave symmetry allows half the actuators of an actuator assembly to execute power strokes as the other half execute retraces. The triangular stroke wave form of the tangenter is composed of cosine and sine terms. Generally, varying the amplitudes of the cosine terms in Fourier proportion varies the tangential force transduced, while varying the amplitudes of the sine terms in Fourier proportion varies the tangential speed of actuation. Cosine and sine groups, being physically distinct and electrically separate, are simultaneously independently electrically controllable. These speed and force controlling methods are preferred over methods that vary frequency, since frequency variation requires more complex circuitry to maintain the benefits of electrical resonance, for example, tune tracking. Lifter group amplitude, corresponding to normal force applied to the bolt by the traction member, and excess stroke needed for traction member clearance during retrace, is varied according to the need to prevent sliding for the predetermined tangential force at each instant. The product of tangential force and power stroke distance is the work done on the bolt, the power being the work done per unit of time averaged over the walking cycle. Similarly, the product of lifter stroke and object lift distance is the work done on the positioned object during the forcing stroke portion, while the power applied to the object is the work done per bolt walking period.

Fourier stimulation affords relatively flexible methods of injecting the energy that is to be converted to mechanical power. A short pulse delivered to the input of each stimulator contains very little more energy than needed to keep each circuit amplitude at the proper Fourier value, to satisfy the operating requirements of the instant, and to replace energy that is being converted to mechanical work. Stimulating pulses are delivered anywhere during the rising portion of each sine or cosine wave, analogous to supplying a downward impulse to a child riding a swing. Stimulation pulse shape is relatively less important than the delivered pulse power. Fourier stimulation affords relatively flexible methods of adapting an actuator system to the electric drive means of a particular application. The coupling factor of the coupling-stimulating means is easily adapted to activate the actuator using a wide variety of electrical sources, such as switched DC, switched AC, conventional power mains, marine or aircraft mains, and power busses of orbital space facilities.

Fourier stimulation provides the relatively high electrical efficiency commonly associated with electrical resonance. Avoiding the use of mechanical resonance precludes the proclivity of elastic resonators to produce only sinusoidal motion, a motion that cannot achieve smooth walking. Smooth walking provides the relatively high mechanical efficiency associated with actuation without sliding. Taken together, Fourier stimulation and smooth walking achieve a system efficiency higher than that achieved by the sole use of either.

The electrical resistance of normal materials causes internal actuator heating. The effective actuator energy density is increased when internal heat generation is prevented, and in proportion to the rate at which internally generated heat is removed. Fluids are forced through interconductor clearances for cooled actuator applications. Heat is more quickly removed from myriad minified conductors because of the relatively large ratio of surface area to volume. Miniature conductors are sufficiently cooled by interconductor forced convection in many applications. Cooled macroscopic actuator embodiments have fluid channels (not illustrated) internal to the conductors. Maximum energy density obtains when all actuator components have internal cooling channels. Piezoelectric actuators do not require forced convection cooling in most applications.

Embodiments having cooling fluid supplied to and removed from internal channels by tubing operate in a vacuum without cooling fluid exposure. Internal cooling microchannels increase the energy density in minified actuator embodiments and are included in the scope of the present invention, despite increased epitaxial fabrication difficulty.